# Buttress Dams

## Best Practices in Dam and Levee Safety Risk Analysis

## Part E – Concrete Structures

## Chapter E-5

## June 2017

US Army Corps of Engineers®

# Outline

- Load Carrying Mechanism and Types
- Case Histories
- Seismic Considerations
- Typical Event Tree (Seismic)
- Reinforcing Steel Considerations
- Hydrodynamic Interaction
- Evaluating Reinforced Concrete Members
- Nonlinear Analysis

# Objectives

- Understand the mechanisms that affect buttress dam failure
- Understand how to construct an event tree to represent buttress dam failure
- Understand how to estimate nodal probabilities and probability of breach

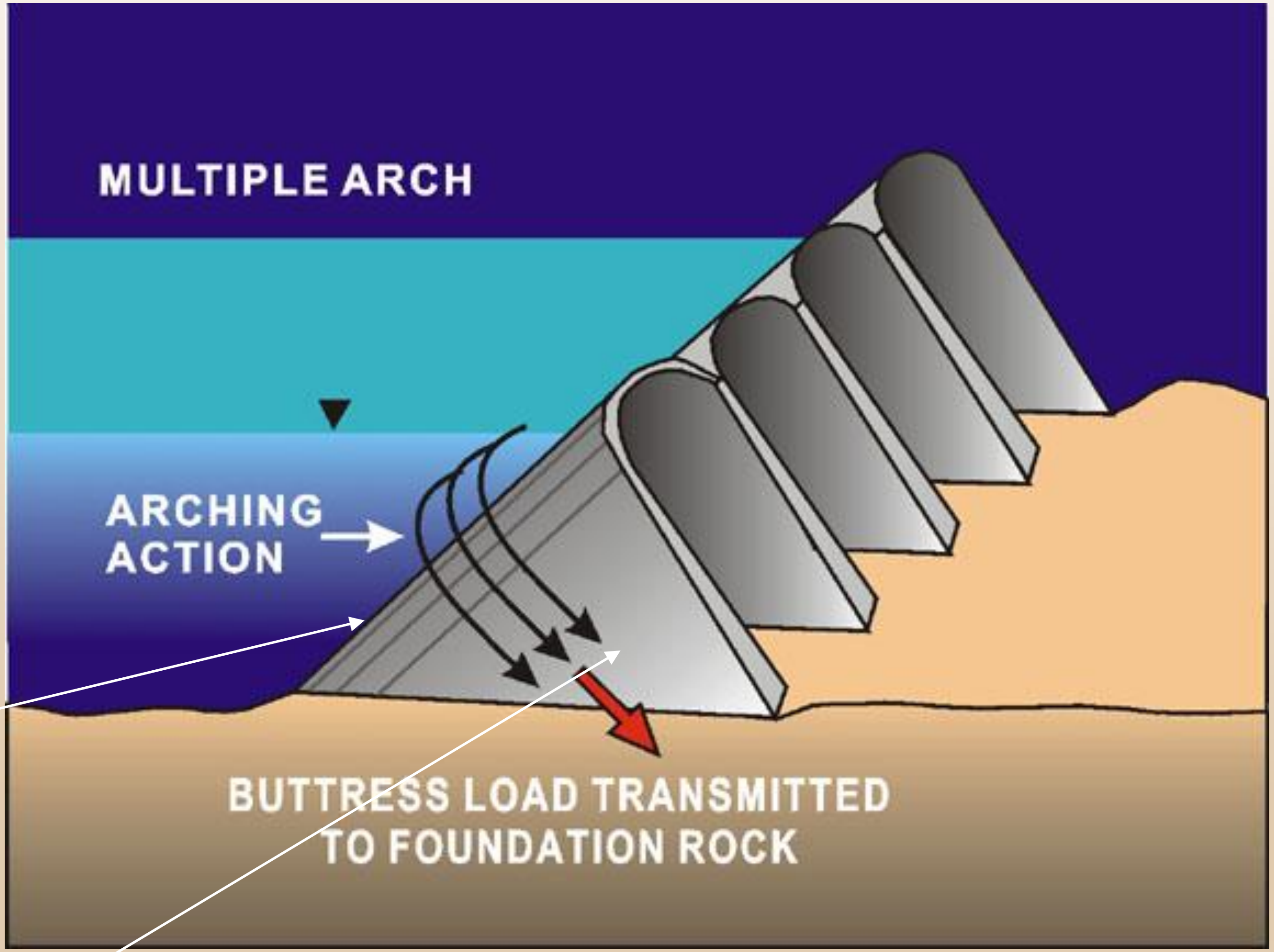
# Key Concepts

- Buttress dams constructed mainly in early $20^{th}$ century when labor was cheap and materials were expensive.
- Buttresses saved on concrete but light structures required upstream sloping water barriers – water force acting downward needed for stability.
- Designed to carry load in stream direction, but did not consider (seismic) loading in cross-stream direction.
- Cracking or yielding of reinforced concrete members does not equal dam failure

# Load Carrying Mechanism and Types

# Buttress Dams

Early 20th century
Expensive materials
Cheap labor
Sloped upstream face needed for stability




Buttresses

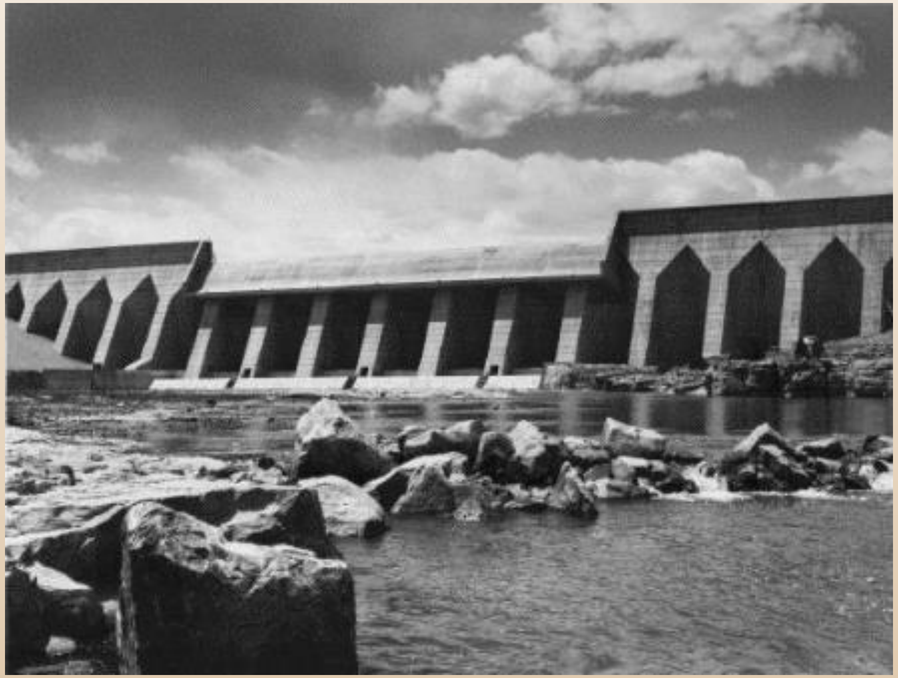
# Slab and Buttress

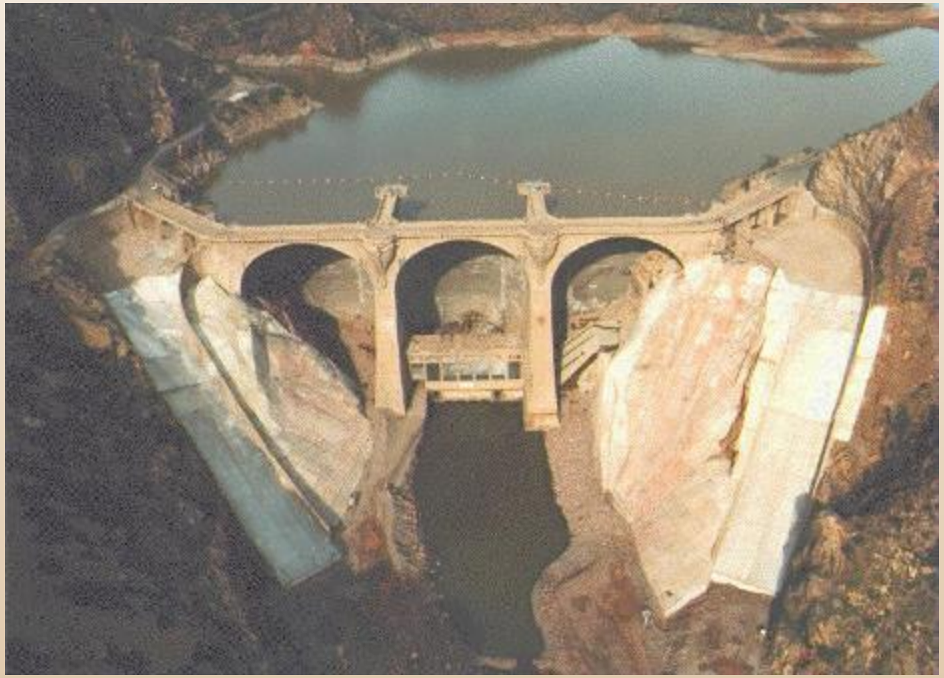
Also known as an Amburesen Dam

# Multiple Arch

# Massive-Head Buttress

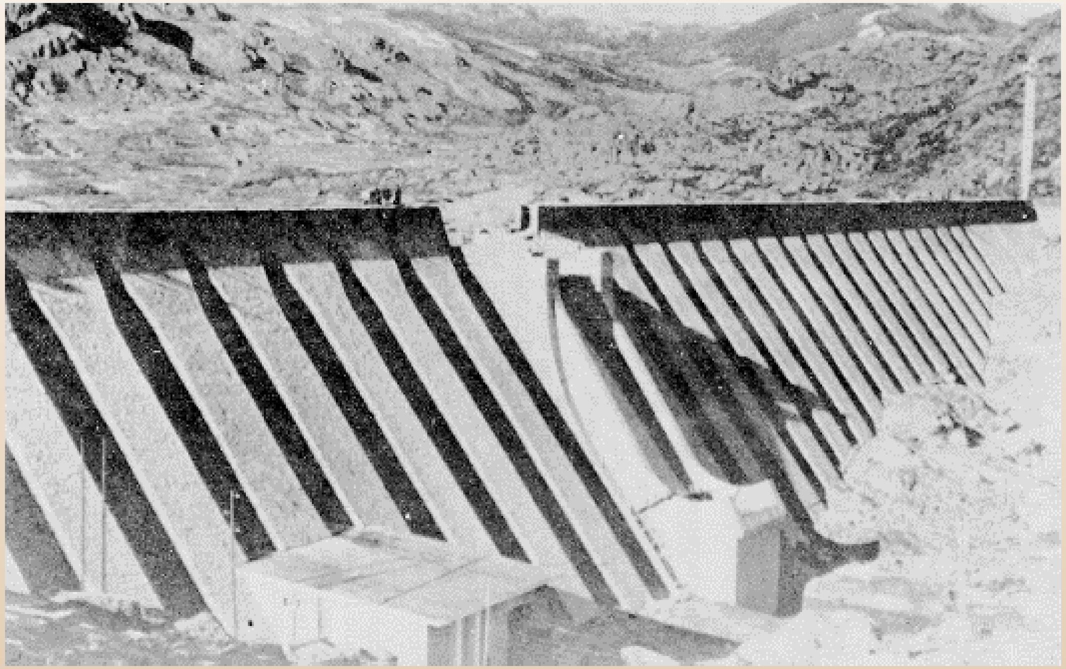
# Domes





# Case Histories

# Vega de Tera Dam, Northwest Spain



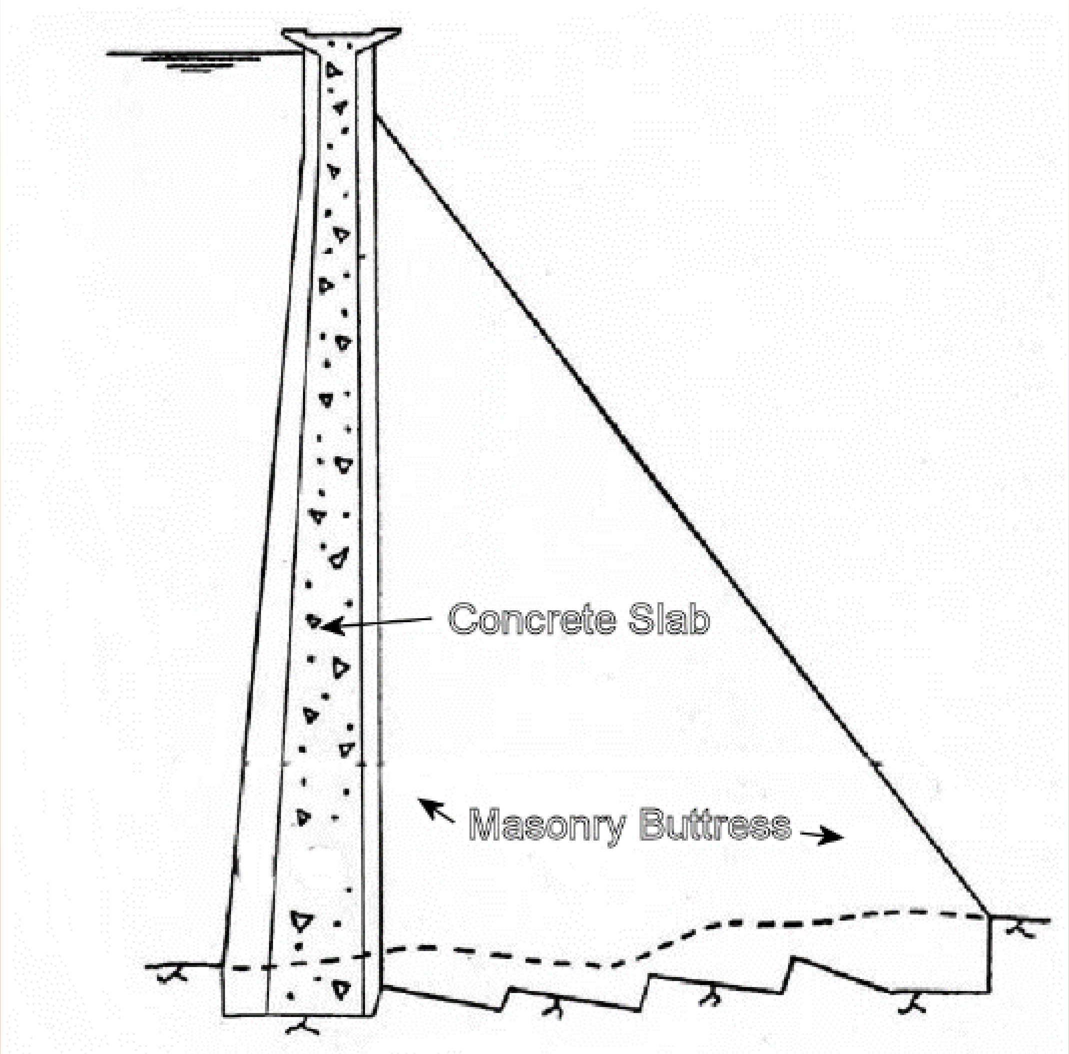
112’ high buttress dam completed 1957

Winter shutdown, little attention to lift joints

Failed January 10, 1959

144 fatalities

# Vega de Tera Dam




**But not much slope on u/s face!**

Buttresses cement mortared masonry

Grouting in 1956 to control leakage

Reservoir full in 1958

Empty in October 1958

In January, heavy rains filled reservoir

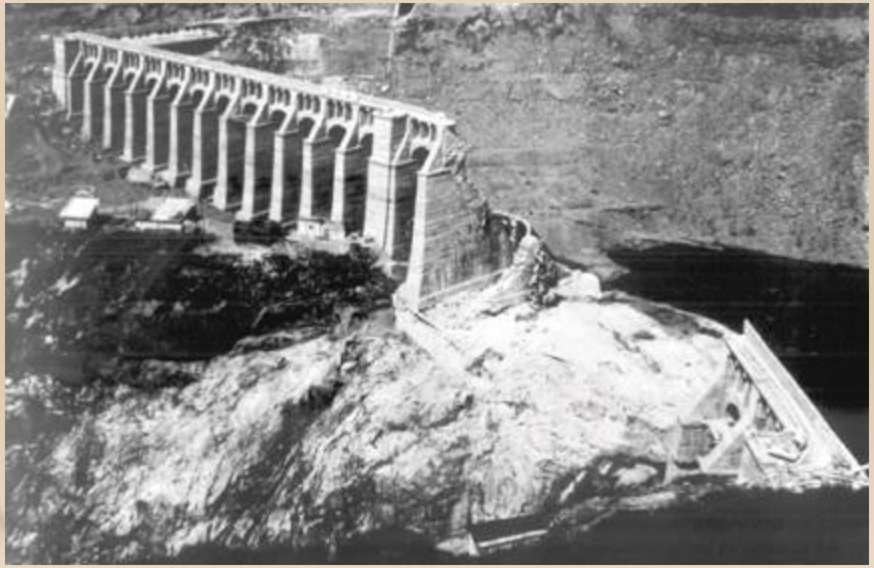
17 buttresses failed in rapid succession

Failure initiated between masonry and concrete on sloping portion of foundation

Modulus of masonry = 140,000 $lb/in^2$

Official cause of failure attributed to large deformations due to low modulus masonry

# Gleno Dam, Italy

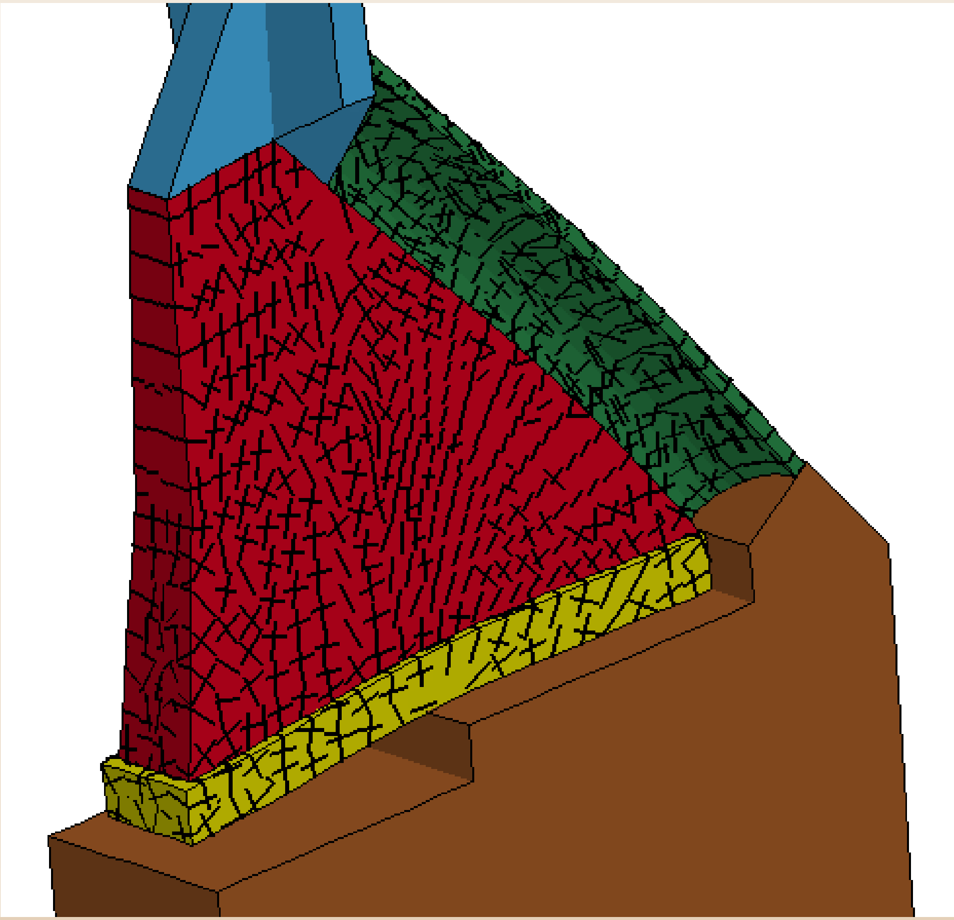


- 164-ft high multiple arch
- 52-foot high masonry plug constructed in deep central gorge (lime mortar instead of specified cement mortar)
- Original design called for gravity dam; design changed and dam built prior to approval
- Poor concrete quality
- Dam survived nearly full for 2 months
- Failed October 22, 1923
- 100-foot high wave, widespread destruction in Dezzo River Valley
- 356 fatalities

# Poor Concrete Quality

# Gleno Dam Failure – Nonlinear FE Model

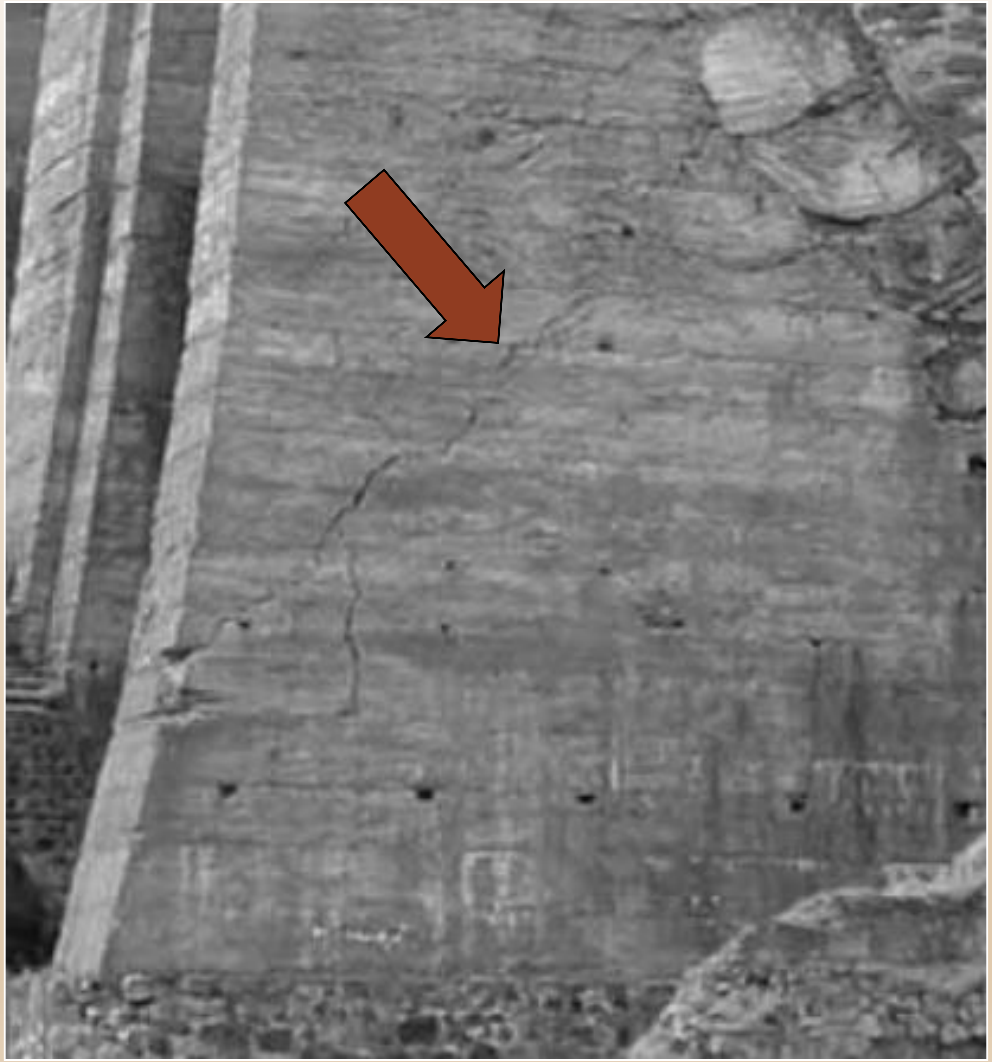
- Official inquiry indicated the masonry plug was not stiff enough nor did it extend far enough downstream to carry the buttress loads.
- With complete loss of contact over the front 35 ft of foundation (representing the downstream portion of the masonry plug), the finite model depicted here fails catastrophically!



# Gleno Dam

Masonry Plug

Model predicted cracking matched observed cracking



# Seismic Considerations

# Typical Event Tree for Seismic Evaluation

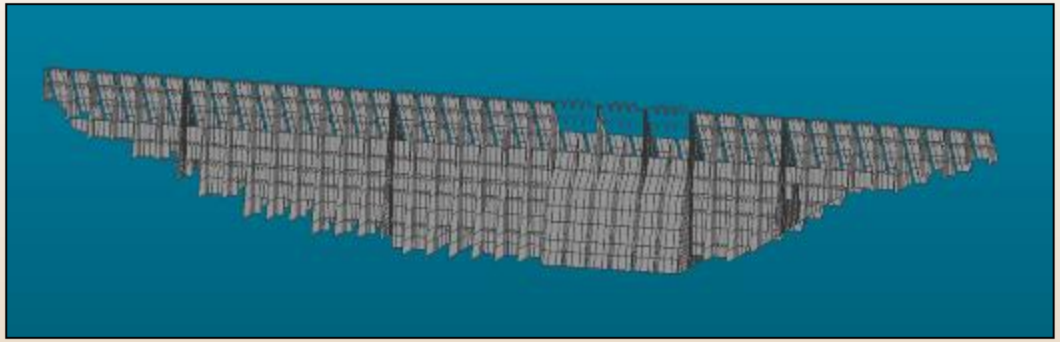
- Reservoir at or above threshold level
  - Cross stream earthquake load range
    - Struts fail in compression
      - Buttress moment capacity exceeded (concrete cracks/reinforcement fails)
        - Buttress buckles or deforms excessively (upstream water barrier lost)
          - Breach outflow loads adjacent buttresses, multiple buttresses fail

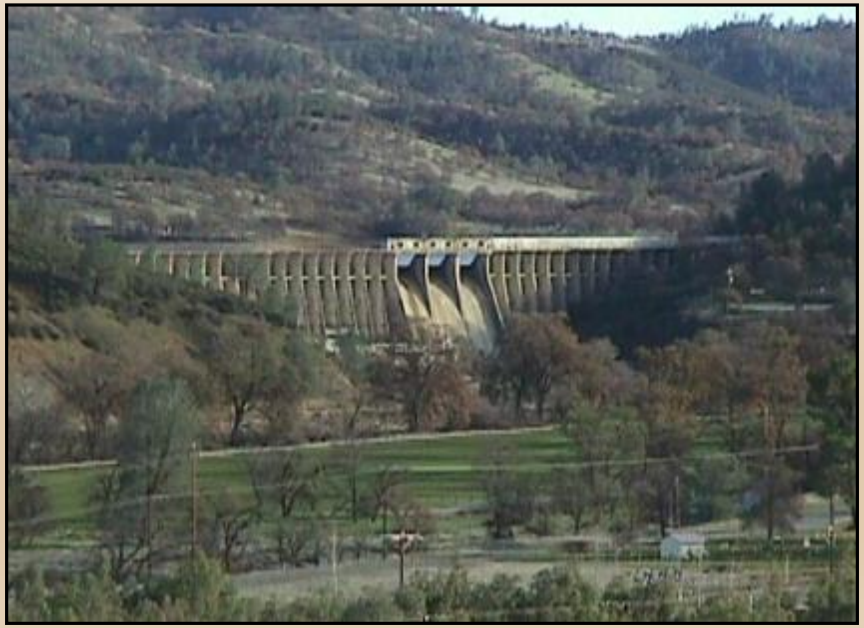
# Water Barrier Evaluation

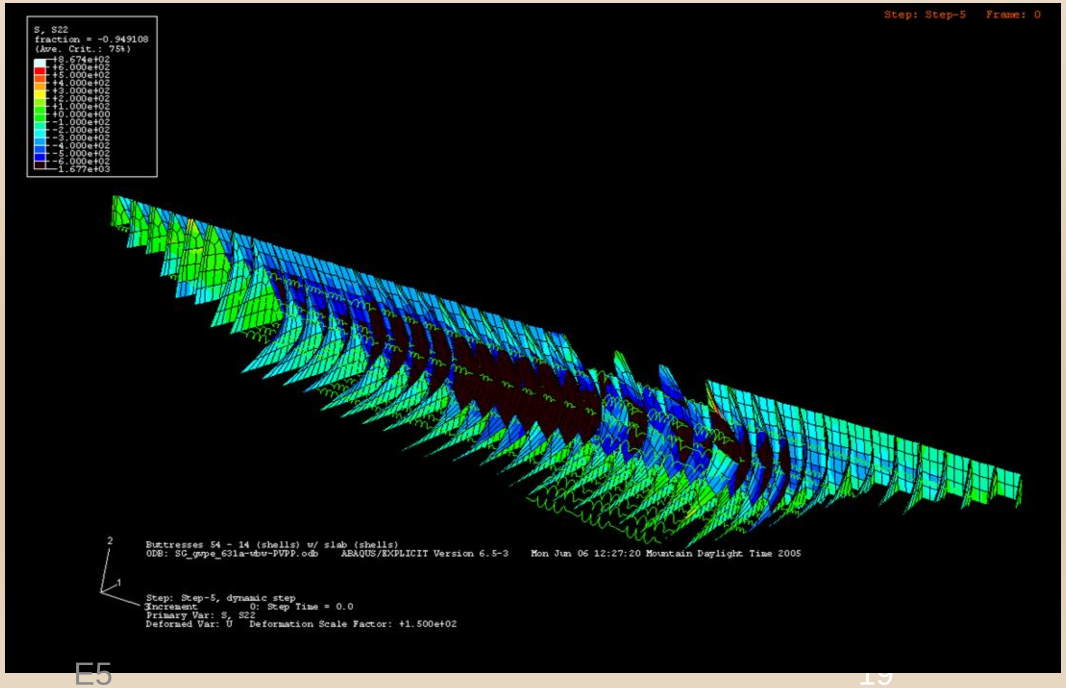
- Note that the previous event tree did not address the upstream slabs/corbels, arches, or domes
- This would be a separate potential failure mode that should be evaluated using reinforced concrete principles (covered in another chapter)

# Buttress Dam Seismic Analysis

- Buttresses weak in cross-canyon direction
- Entire dam must be modeled to include “racking”







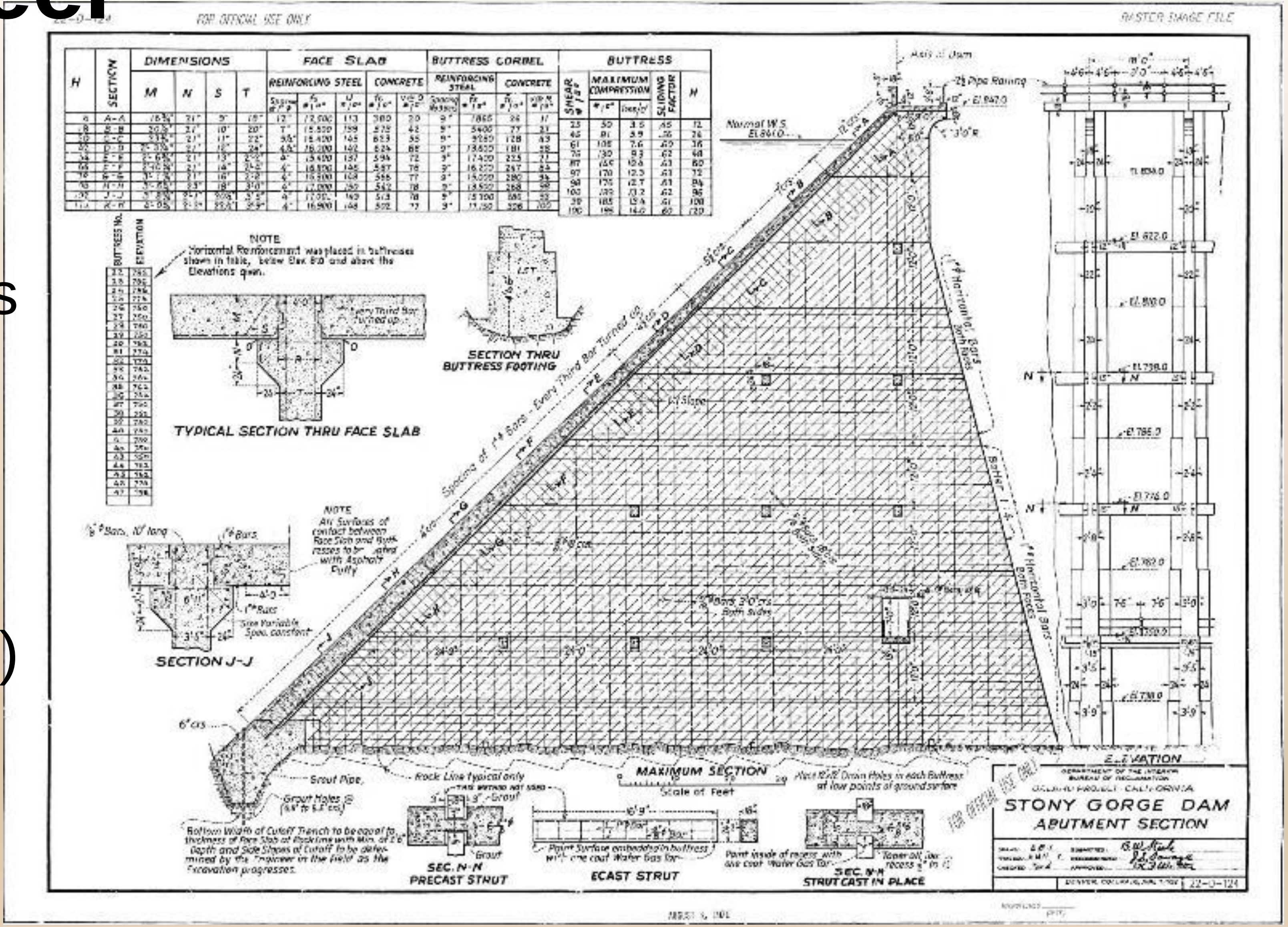
# Analysis Progression

- Note: Although buttress dams typically require a 3-D finite element analysis to draw any meaningful conclusions, initial analyses should be as simple as possible (e.g. linear-elastic, massless foundation and added mass for hydrodynamic interaction) and progress to more sophisticated analyses as needed.

# Reinforcing Steel

Most buttress dams are getting old, concrete spalls or cracking can lead to corrosion

Also no air entrainment (freeze-thaw susceptibility) and reinforcement not up to current standards



# Hydrodynamic Interaction, Stream Direction

The hydrodynamic forces are reduced by the sloping face (the water will tend to ride up along the face). Zangar approach (below) can be used with directional masses.

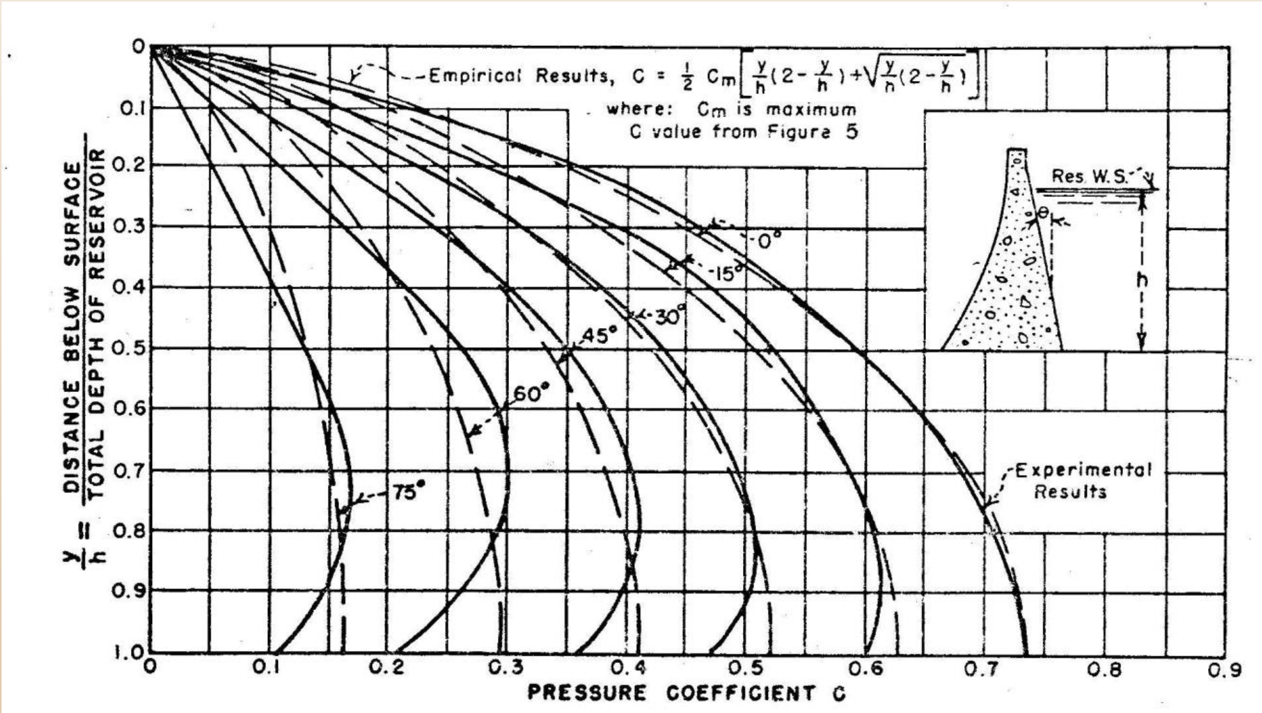



FIGURE 6 - Comparison of experimental and empirical pressure distribution curves.

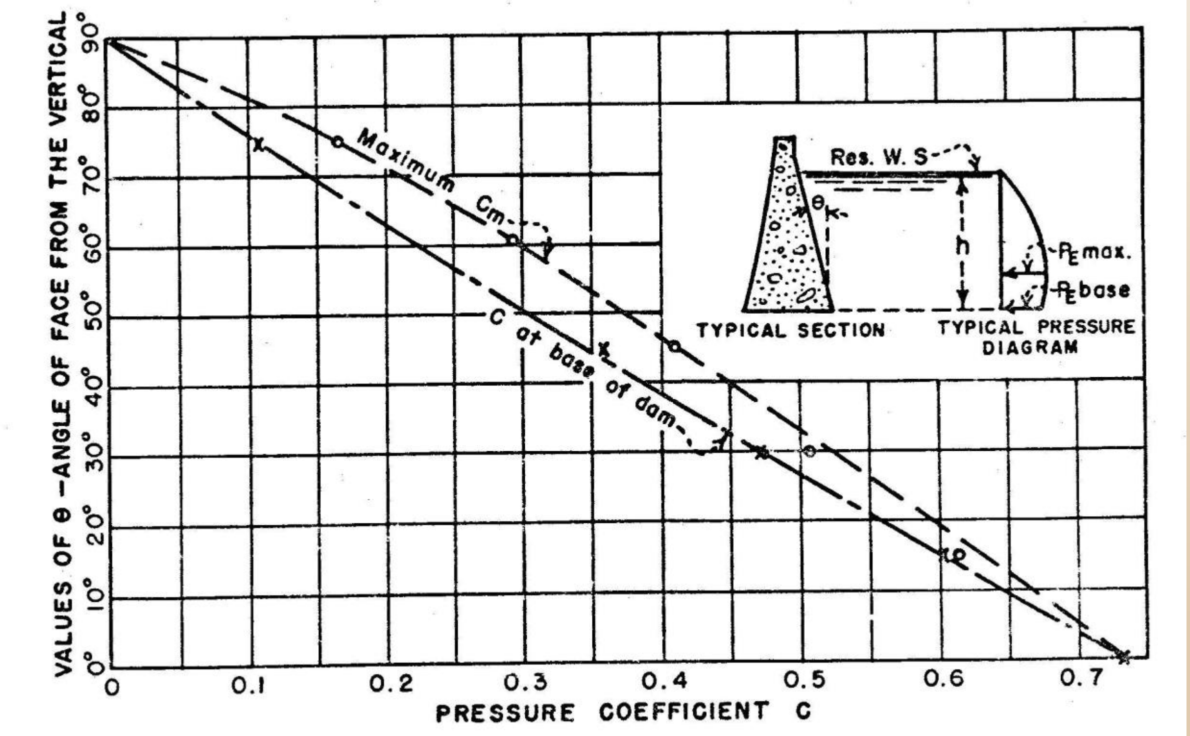
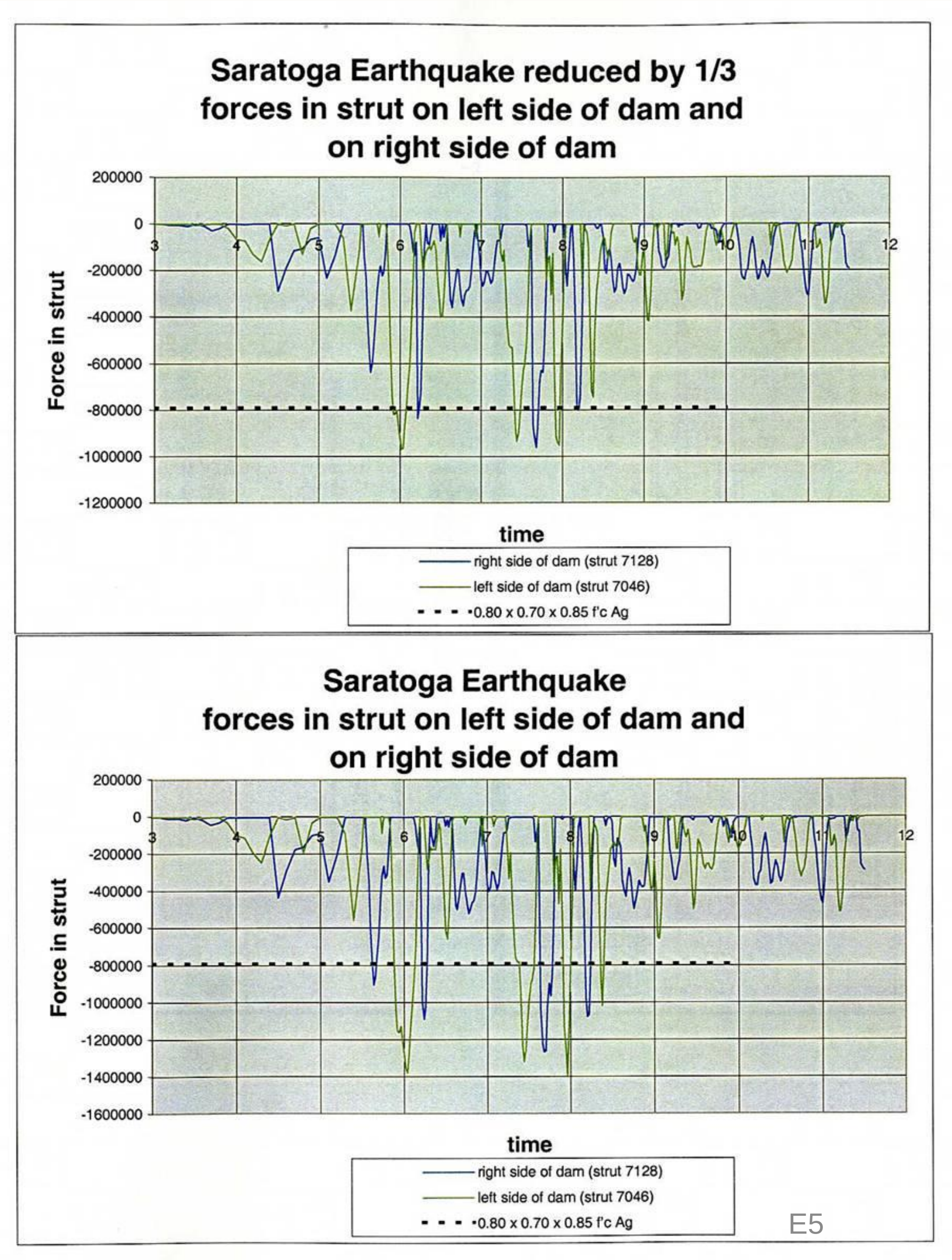



FIGURE 5 - Pressure coefficients for constant sloping faces.

Or use fluid elements, if available

# Struts




Some buttresses have struts between buttresses for lateral support

As buttresses move in earthquake, load accumulates across dam and can overload end struts (push over analysis)

Crushing stress in struts normally controls over buckling

# Condition of Struts during 10k Motions

Struts for which output was requested:

| Buttress | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 | 51 | 52 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Elevation 822 | 7002 | 7003 | 7004 | 7005 | 7006 | 7007 | 7008 | 7009 | 7010 | 7011 | 7012 | 7013 | | | | | | | 7020 | 7021 | 7022 | 7023 | 7024 | 7025 | 7026 | 7027 | 7028 | 7029 | 7030 | 7031 | 7032 | 7033 | 7034 | 7035 | 7036 | 7037 | 7038 | 7039 | 7040 |
| Elevation 798 ds | | | | | | 7045 | 7046 | 7047 | 7048 | 7049 | 7050 | 7051 | 7052 | 7053 | 7054 | 7055 | 7056 | 7057 | 7058 | 7059 | 7060 | 7061 | 7062 | 7063 | 7064 | 7065 | 7066 | 7067 | 7068 | 7069 | 7070 | 7071 | 7072 | 7073 | 7074 | 7075 | 7259 | 7261 | |
| Elevation 798 us | | | | | | | | 7076 | 7077 | 7078 | 7079 | 7080 | 7081 | 7082 | 7083 | 7084 | 7085 | 7086 | 7087 | 7088 | 7089 | 7090 | 7091 | 7092 | 7093 | 7094 | 7095 | 7096 | 7097 | 7098 | 7099 | 7100 | 7101 | 7102 | 7103 | 7104 | 7260 | | |
| Elevation 774 ds | | | | | | | | 7253 | 7105 | 7106 | 7107 | 7108 | 7109 | 7110 | 7111 | 7112 | 7113 | 7114 | 7115 | 7116 | 7117 | 7118 | 7119 | 7120 | 7121 | 7122 | 7123 | 7124 | 7125 | 7126 | 7127 | 7128 | 7256 | | | | | | |
| Elevation 774 | | | | | | | | 7254 | 7129 | 7130 | 7131 | 7132 | 7133 | 7134 | 7135 | 7136 | 7137 | 7138 | 7139 | 7140 | 7141 | 7142 | 7143 | 7144 | 7145 | 7146 | 7147 | 7148 | 7149 | 7150 | 7151 | 7152 | 7257 | | | | | | |
| Elevation 774 us | | | | | | | | 7255 | 7153 | 7154 | 7155 | 7156 | 7157 | 7158 | 7159 | 7160 | 7161 | 7162 | 7163 | 7164 | 7165 | 7166 | 7167 | 7168 | 7169 | 7170 | 7171 | 7172 | 7173 | 7174 | 7175 | 7176 | 7258 | | | | | | |
| Elevation 750 ds | | | | | | | | | | 7249 | 7177 | 7178 | 7179 | 7180 | 7181 | 7182 | 7183 | 7184 | 7185 | 7186 | 7187 | 7188 | 7189 | 7190 | 7191 | 7192 | 7193 | 7194 | | | | | | | | | | | |
| Elevation 750 | | | | | | | | | | 7250 | 7195 | 7196 | 7197 | 7198 | 7199 | 7200 | 7201 | 7202 | 7203 | 7204 | 7205 | 7206 | 7207 | 7208 | 7209 | 7210 | 7211 | 7212 | | | | | | | | | | | |
| Elevation 750 | | | | | | | | | | 7252 | 7213 | 7214 | 7215 | 7216 | 7217 | 7218 | 7219 | 7220 | 7221 | 7222 | 7223 | 7224 | 7225 | 7226 | 7227 | 7228 | 7229 | 7230 | | | | | | | | | | | |
| Elevation 750 us | | | | | | | | | | 7251 | 7231 | 7232 | 7233 | 7234 | 7235 | 7236 | 7237 | 7238 | 7239 | 7240 | 7241 | 7242 | 7243 | 7244 | 7245 | 7246 | 7247 | 7248 | | | | | | | | | | | |

Struts selected for time history output

First struts removed (Saratoga EQ)
(due to exceedance of capacity at first pulse)

| Buttress | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 | 51 | 52 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Elevation 822 | 7002 | 7003 | 7004 | 7005 | 7006 | 7007 | 7008 | 7009 | 7010 | 7011 | 7012 | 7013 | | | | | | | 7020 | 7021 | 7022 | 7023 | 7024 | 7025 | 7026 | 7027 | 7028 | 7029 | 7030 | 7031 | 7032 | 7033 | 7034 | 7035 | 7036 | 7037 | 7038 | 7039 | 7040 |
| Elevation 798 ds | | | | | | 7045 | 7046 | 7047 | 7048 | 7049 | 7050 | 7051 | 7052 | 7053 | 7054 | 7055 | 7056 | 7057 | 7058 | 7059 | 7060 | 7061 | 7062 | 7063 | 7064 | 7065 | 7066 | 7067 | 7068 | 7069 | 7070 | 7071 | 7072 | 7073 | 7074 | 7075 | 7259 | 7261 | |
| Elevation 798 us | | | | | | | | 7076 | 7077 | 7078 | 7079 | 7080 | 7081 | 7082 | 7083 | 7084 | 7085 | 7086 | 7087 | 7088 | 7089 | 7090 | 7091 | 7092 | 7093 | 7094 | 7095 | 7096 | 7097 | 7098 | 7099 | 7100 | 7101 | 7102 | 7103 | 7104 | 7260 | | |
| Elevation 774 ds | | | | | | | | 7253 | 7105 | 7106 | 7107 | 7108 | 7109 | 7110 | 7111 | 7112 | 7113 | 7114 | 7115 | 7116 | 7117 | 7118 | 7119 | 7120 | 7121 | 7122 | 7123 | 7124 | 7125 | 7126 | 7127 | 7128 | 7256 | | | | | | |
| Elevation 774 | | | | | | | | 7254 | 7129 | 7130 | 7131 | 7132 | 7133 | 7134 | 7135 | 7136 | 7137 | 7138 | 7139 | 7140 | 7141 | 7142 | 7143 | 7144 | 7145 | 7146 | 7147 | 7148 | 7149 | 7150 | 7151 | 7152 | 7257 | | | | | | |
| Elevation 774 us | | | | | | | | 7255 | 7153 | 7154 | 7155 | 7156 | 7157 | 7158 | 7159 | 7160 | 7161 | 7162 | 7163 | 7164 | 7165 | 7166 | 7167 | 7168 | 7169 | 7170 | 7171 | 7172 | 7173 | 7174 | 7175 | 7176 | 7258 | | | | | | |
| Elevation 750 ds | | | | | | | | | | 7249 | 7177 | 7178 | 7179 | 7180 | 7181 | 7182 | 7183 | 7184 | 7185 | 7186 | 7187 | 7188 | 7189 | 7190 | 7191 | 7192 | 7193 | 7194 | | | | | | | | | | | |
| Elevation 750 | | | | | | | | | | 7250 | 7195 | 7196 | 7197 | 7198 | 7199 | 7200 | 7201 | 7202 | 7203 | 7204 | 7205 | 7206 | 7207 | 7208 | 7209 | 7210 | 7211 | 7212 | | | | | | | | | | | |
| Elevation 750 | | | | | | | | | | 7252 | 7213 | 7214 | 7215 | 7216 | 7217 | 7218 | 7219 | 7220 | 7221 | 7222 | 7223 | 7224 | 7225 | 7226 | 7227 | 7228 | 7229 | 7230 | | | | | | | | | | | |
| Elevation 750 us | | | | | | | | | | 7251 | 7231 | 7232 | 7233 | 7234 | 7235 | 7236 | 7237 | 7238 | 7239 | 7240 | 7241 | 7242 | 7243 | 7244 | 7245 | 7246 | 7247 | 7248 | | | | | | | | | | | |

Struts removed due to exceedance of capacity at first pulse of Saratoga Record

From analysis with above struts removed,
the following additional struts reached loads exceeding capacity

| Buttress | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 | 51 | 52 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
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| Elevation 798 ds | | | | | | 7045 | 7046 | 7047 | 7048 | 7049 | 7050 | 7051 | 7052 | 7053 | 7054 | 7055 | 7056 | 7057 | 7058 | 7059 | 7060 | 7061 | 7062 | 7063 | 7064 | 7065 | 7066 | 7067 | 7068 | 7069 | 7070 | 7071 | 7072 | 7073 | 7074 | 7075 | 7259 | 7261 | |
| Elevation 798 us | | | | | | | | 7076 | 7077 | 7078 | 7079 | 7080 | 7081 | 7082 | 7083 | 7084 | 7085 | 7086 | 7087 | 7088 | 7089 | 7090 | 7091 | 7092 | 7093 | 7094 | 7095 | 7096 | 7097 | 7098 | 7099 | 7100 | 7101 | 7102 | 7103 | 7104 | 7260 | | |
| Elevation 774 ds | | | | | | | | 7253 | 7105 | 7106 | 7107 | 7108 | 7109 | 7110 | 7111 | 7112 | 7113 | 7114 | 7115 | 7116 | 7117 | 7118 | 7119 | 7120 | 7121 | 7122 | 7123 | 7124 | 7125 | 7126 | 7127 | 7128 | 7256 | | | | | | |
| Elevation 774 | | | | | | | | 7254 | 7129 | 7130 | 7131 | 7132 | 7133 | 7134 | 7135 | 7136 | 7137 | 7138 | 7139 | 7140 | 7141 | 7142 | 7143 | 7144 | 7145 | 7146 | 7147 | 7148 | 7149 | 7150 | 7151 | 7152 | 7257 | | | | | | |
| Elevation 774 us | | | | | | | | 7255 | 7153 | 7154 | 7155 | 7156 | 7157 | 7158 | 7159 | 7160 | 7161 | 7162 | 7163 | 7164 | 7165 | 7166 | 7167 | 7168 | 7169 | 7170 | 7171 | 7172 | 7173 | 7174 | 7175 | 7176 | 7258 | | | | | | |
| Elevation 750 ds | | | | | | | | | | 7249 | 7177 | 7178 | 7179 | 7180 | 7181 | 7182 | 7183 | 7184 | 7185 | 7186 | 7187 | 7188 | 7189 | 7190 | 7191 | 7192 | 7193 | 7194 | | | | | | | | | | | |
| Elevation 750 | | | | | | | | | | 7250 | 7195 | 7196 | 7197 | 7198 | 7199 | 7200 | 7201 | 7202 | 7203 | 7204 | 7205 | 7206 | 7207 | 7208 | 7209 | 7210 | 7211 | 7212 | | | | | | | | | | | |
| Elevation 750 | | | | | | | | | | 7251 | 7213 | 7214 | 7215 | 7216 | 7217 | 7218 | 7219 | 7220 | 7221 | 7222 | 7223 | 7224 | 7225 | 7226 | 7227 | 7228 | 7229 | 7230 | | | | | | | | | | | |
| Elevation 750 us | | | | | | | | | | 7252 | 7239 | 7240 | 7241 | 7242 | 7243 | 7244 | 7245 | 7246 | 7247 | 7248 | | | | | | | | | | | | | | | | | | | |

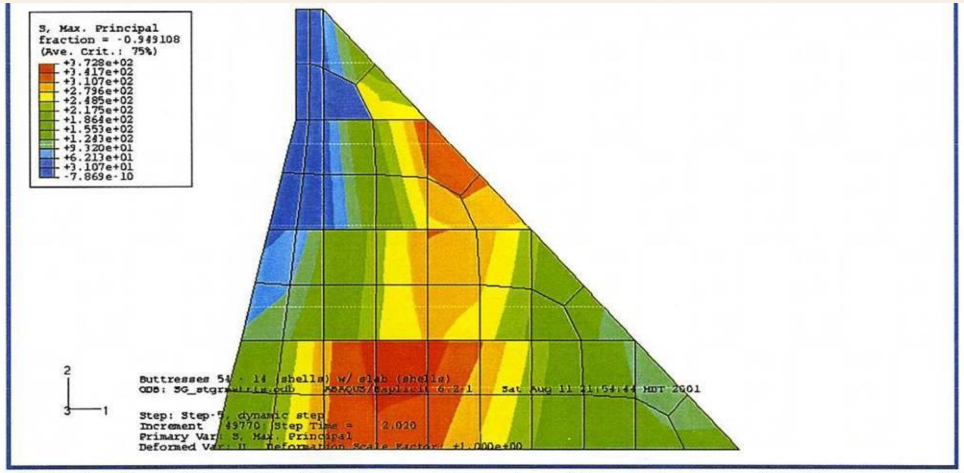
Struts removed due to exceedance of capacity at first pulse (red) of Saratoga Record

Additional struts exceeding capacity (blue)

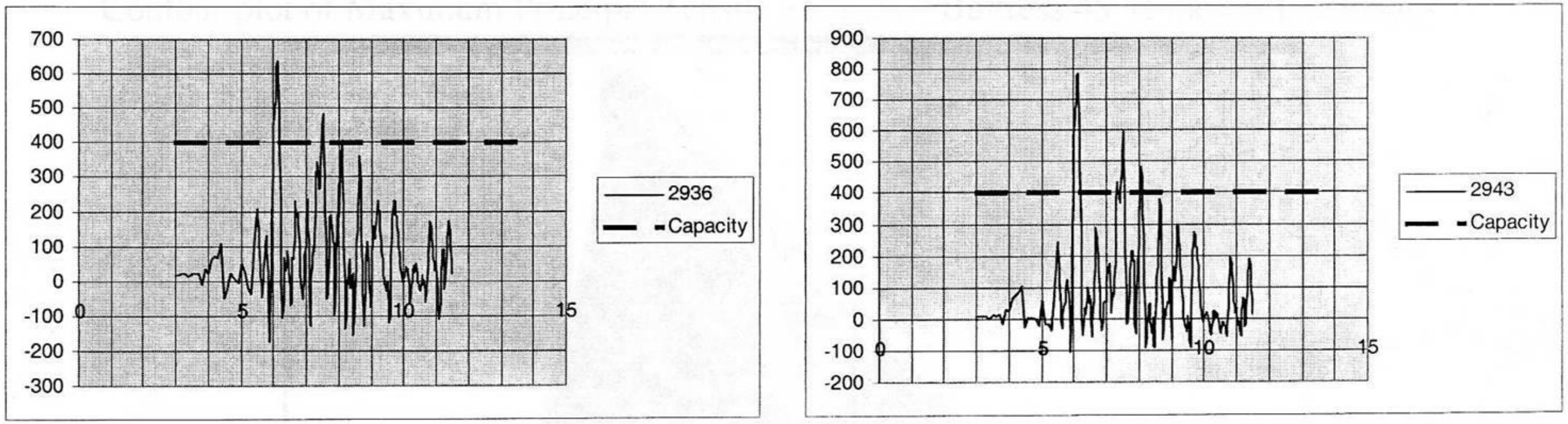
Struts for which forces were reduced (purple)

- Output Selected
- 1st failures removed
- 2nd failures removed
- 2nd near failures removed

# Condition of Buttresses




Contour plot of Maximum Principal Tensile Stresses following Strut Removal – Buttress 45 (time= 7.52 sec)
Saratoga Ground Motions




Time history plot of Maximum Principal Tensile Stresses following Strut Removal – Buttress 25

# Moments

As a result of buttress dams varying in thickness and reinforcement from base to crest, the response of the dam and moments in the buttresses will vary.

Seismically Induced Moments in Buttress

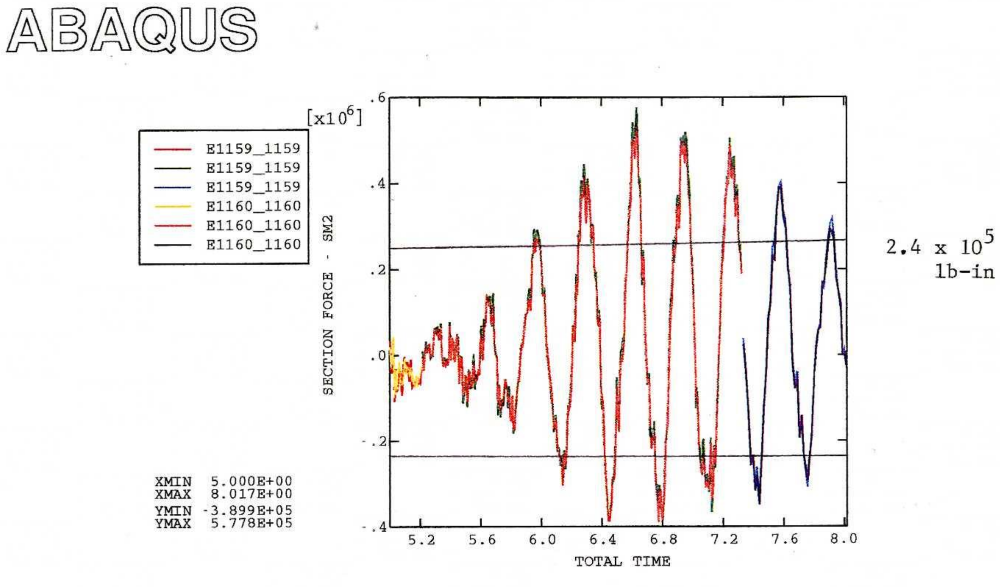
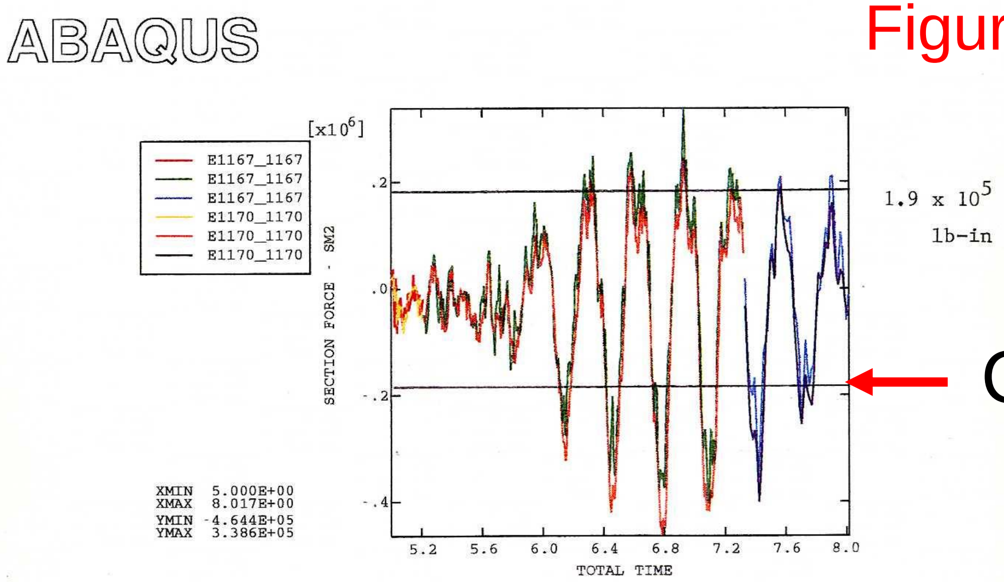



Figure 25a-1 Buttress thickness = 32 inches

Moment History Figures

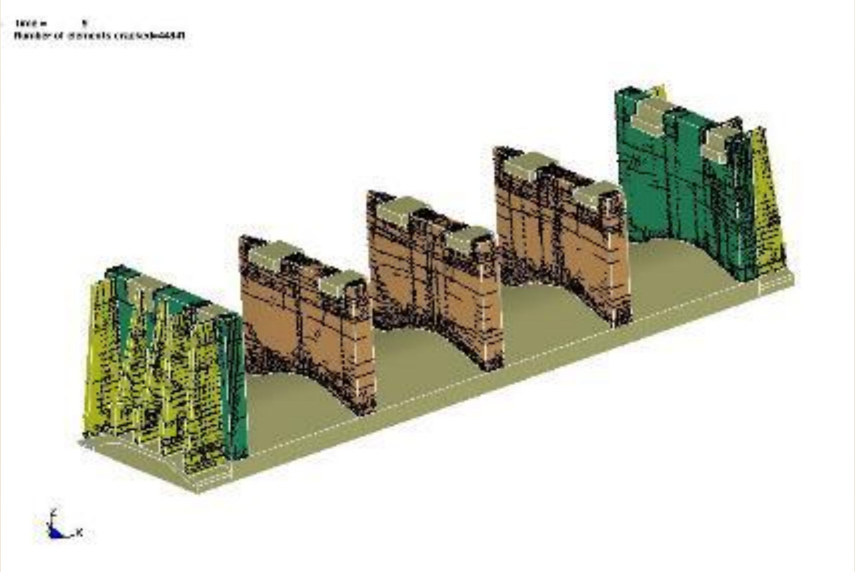


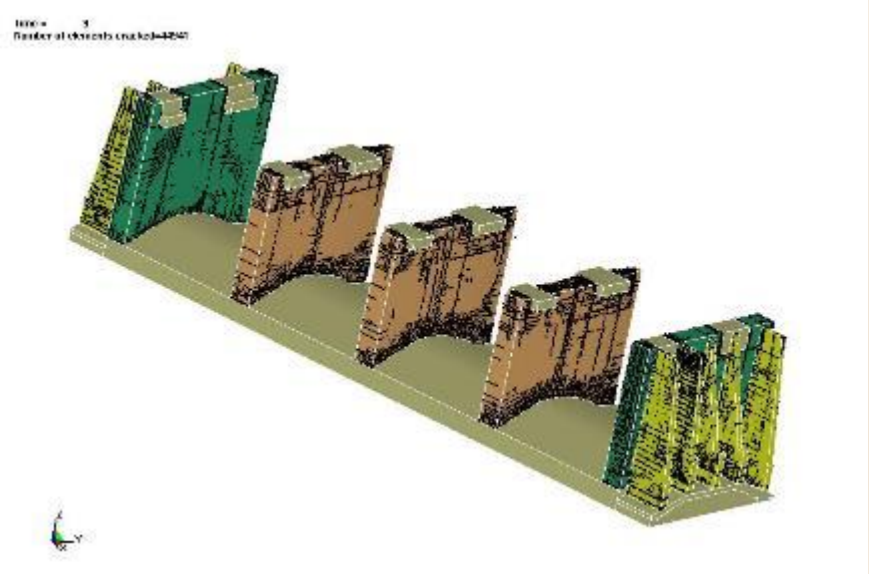

Capacity

Figure 25a-2 Buttress thickness = 26 inches

# Nonlinear Structural Analysis

- Some nonlinear finite element programs have concrete cracking and steel reinforcement models that can be used to examine the potential for cracking, yielding, excessive deformation and failure directly.  However, remember these are just models and careful scrutiny of the input assumptions and output is necessary.





# Takeaway Points

- Buttress dams designed to carry load in the stream direction
- Buttress dams are vulnerable to cross-stream seismic loads
- Finite element analyses of entire structure are needed to capture response
- Reinforced concrete risk concepts can be used to examine probability of nodal estimates
- Careful consideration of the concrete quality, joint treatment, and reinforcing details are required
- Level of analysis for estimating performance of the buttress dam needs to be commensurate with the level of study needed for the risk analysis and decision-making

# Questions or Comments?

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TVA